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SUMMARY REPORT

RESEARCH ON THE HYDROLOGY AND WATER QUALITY OF WATERSHEDS SUBJECTED TO SURFACE MINING

PHASE I:

PREMINING HYDROLOGIC AND WATER QUALITY CONDITIONS

Developed for the

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By

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Science and Education Administration

Agricultural Research

North Appalachian Experimental Watershed

Coshocton, Ohio

and

OHIO AGRICULTURAL RESEARCH AND DEVELOPMENT CENTER

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16. Abstract

Five watersheds, ranging in size from 29 to 52 acres, were selected in east-central Ohio for the purpose of investigating the hydologic and water quality conditions occurring before, during and after surface mining.

The average concentrations of the water quality parameters for all watersheds were as low as or lower than the EPA recommended maximum allowable concentrations in drinking water except for suspended solids. Before mining the average concentration of suspended solids in storm runoff ranged from 118 to 1110 mg/1, and for base flow the range was from 44 to 247 mg/1; the higher concentrations were associated with the watersheds exhibiting the greatest premining disturbance. Iron ranged from an average of less than 3 µg/1 to 228 µg/1. Manganese ranged from less than 41 µg/1 to 334 µg/1.

Premining ground-water systems for each watershed were found to have two major perched aquifers within the top 250 feet. Recharge is mostly from local precipitation and discharge is mostly as spring flow, stream baseflow, evapotranspiration, or leakage through the underlying confining bed. Shallowest ground water is commonly of the calcium bicarbonate type; whereas, water in the deeper aquifers is of variable type. Although dissolved-solids concentration is generally 200-600 mg/1, brackish or salty ground water is present in several areas.

A one-dimensional unsaturated flow model was developed for interfacing with a quasi-three-dimensional ground water model as part of a projected composite hydrologic model. The unsaturated flow model includes provisions for an evapotranspiration model.

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FOREWORD

This report was edited by Gary E. McIntosh, United States Bureau of Mines; and W. R. Hamon, United States Department of Agriculture (USDA) - Science and Education Administration (SEA). The project work was conducted by the Ohio Agricultural Research and Development Center (OARDC) and the USDA-SEA-Agricultural Research (AR), under U. S. Bureau of Mines contracts J0166054 (OARDC) and J0166055 (USDA-SEA-AR), with cooperative contributions by the United States Geological Survey (USGS), the Soil Conservation Service (SCS) and the Utah State University. The contracts were initiated under the Mining Environmental Research Program. They were administered under the technical direction of the Denver Mining Research Center with Gary McIntosh acting as the Technical Project Officer. Francis M. Naughton was the contract administrator for the Bureau of Mines.

This report is a summary of work done during the period of January 22, 1976 to January 22, 1978. The complete report ("Research on the Hydrology and Water Quality of Watersheds Subjected to Surface Mining - Phase I: Premining Hydrologic and Water Quality Conditions") is available on open file from the following sources:

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A limited number of copies of the complete report are available from the following sources:

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U.S. Geological Survey

J. E. Helgesen E. J. Weiss	Ground water hydrology, quality, and modeling

Utah State University

R. W. Jeppson	Unsaturated flow and composite model development

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This report contains no patentable information.

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SUMMARY

A total of five watersheds located in east-central Ohio were selected, ranging in size from 29 to 52 acres and the effects of surface mining and reclamation on hydrology and water quality studied. In order to adequately evaluate the hydrology and water quality aspects of watersheds subjected to surface mining, weather and surface and subsurface hydrologic data are required. Also, for the modeling of watershed hydrology and water quality, spatial, and temporal and numerical descriptions of the hydrologic and water quality components are necessary. The hydrologic data collection system for each watershed is designed to meet these needs.

The period of pre-mining record for each watershed varied as instruments were installed and mining progressed. In general, complete data for the pre-mining conditions were obtained over a period of 10 months for Watershed C06 and about 8 months for Watershed M09. Such data continues to be collected for Watershed A06 (not to be mined) and for Watershed J11 (yet to be mined).

Precipitation occurring during the study period departed from the long term average at the C06, M09 and J11 sites by +1, -8, and +19 percent, respectively. For the long term period (30 months) at the A06 site, the departure was only +3 percent. In general, the seasonal precipitation was not very representative of the long term averages.

Infiltration capacity data were obtained for three soils by use of a rainfall simulator-infiltrometer system. The time domain of infiltration was representable by a three parameter equation, in the form of an analogous resistance-capacitance circuit. The maximum infiltration rates ranged from 1.95 to 4.12 and the equilibrium rates from 0.47 to 1.25 inches per hour. The time constant of the diminishing infiltration ranged from 0.24 to 1.0 hour.

Spring flows at the C06, M09, and A06 sites were nearly constant for short periods of time and ceased at the C06 and M09 sites in the fall. Maximum average daily flow rates were 0.0052, 0.0032, and 0.0444 cubic feet per second (cfs) for sites C06, M09, and A06, respectively.

Runoff for the A06 index watershed was erratic during the comparable year of 1977 with a yearly excess of 3 percent over normal. The portion of precipitation occurring as surface runoff amounted to 30, 12, 8, and 35 percent for watersheds C06, M09, J11 and A06, respectively. Peak discharges observed for the period were 5.86, 81.95, 6.31, and 13.80 cfs for watersheds C06, M09, J11 and A06, respectively. Runoff from the small watersheds was rather low, ranging from less than one to only 4 percent of the precipitation.

Base flow and runoff water samples from four of the un-mined watersheds (C06, M09, J11 and A06) were collected and analyzed quantitatively for 39 water quality parameters. In addition, sediment fractions of the base flow and runoff and monthly precipitation samples were analyzed for 17 and 23 parameters, respectively.

Considering the average concentrations of different water quality parameters in water samples from four watersheds, it is evident that the concentrations were as low or lower than the recent U. S. Environmental Protection Agency recommended maximum concentrations in drinking water.

The average concentrations of suspended solids in runoff were 870, 1110, 118, and 144 mg/l (ppm) for Watersheds C06, M09, J11, and A06, respectively. For base flow, concentrations of 247, 157, 44, and 45 mg/l were observed for the watersheds in the same order as above. Watershed C06 experienced some road construction for installation of wells; M09 and not completely recovered from the development of a well which involved an access road; J11 has a gravel road for part of its upper boundary with an access road in the upper reaches;, and A06, the least disturbed and wooded, has an old gravel road on the eastern slope and experienced only minor disturbance at one well development site.

The analyses of monthly precipitation samples revealed that the concentrations of several parameters in precipitation equaled or exceeded the levels of corresponding parameters in runoff water.

Core-hole and drill-hole information shows that two major perched saturated zones (aquifers) underlie each watershed. Relatively impermeable clays or shales that underlie coal seams serve as the basis for these aquifers. Generally, these two aquifers involve local flow systems, whereas deeper ground water is part of more regional systems. Top aquifer ground water in each watershed is recharged from precipitation and moves downward or laterally toward the coal outcrop; discharge is as spring flow, evapotranspiration, or downward leakage through the underclay. The middle aquifer receives some recharge directly from precipitation and some from leakage through the clay above it. Discharge is mostly as stream base flow, evapotranspiration, or downward leakage. Underflow across watershed boundaries occurs in the deep aquifers and in parts of the perched aquifers at M09 and A06. Ground-water levels, spring flow, and stream flow follow seasonal trends in precipitation. However, direct response to individual precipitation or snowmelt events is not evident because of the time needed for percolation through unsaturated zones.

Ground-water quality varies considerable between and within watersheds. Much of the shallowest ground water is of the calcium bicarbonate type; deeper water is of diverse water types and is generally more mineralized. Although dissolved-solids concentration is commonly 200-6-0 mg/l, brackish or salty waters occur in parts of the middle and deep aquifers of M09 and A06. Hardness of most ground water is 150-300 mg/l and pH is 6.5-8.0.

The modeling effort was directed toward watershed hydrology, without water quality components. Water quality will be incorporated into the model subsequently by utilizing the hydrology as determined by the hydrologic model as its basis. This model will consist of several sub-models which will be linked together to provide a composite model for simulation of the hydrology within and on the watershed surface. The submodels will consist of a ground-water model, an unsaturated flow model, an overland flow model, and an evapotranspiration model.

The watersheds under consideration in this study have two perched water tables above the clay layer which lies under the coal beds, thus, there are two separate unsaturated zones in the pre-mined condition. The ground-water model is structured on a grid network and the unsaturated zone is divided into overlying prismatic elements for numerical solution. The unsaturated water movement in each such element will be considered to be one-dimensional in the vertical direction. Lateral movement will be restricted to the surface and ground-water flows.

An unsaturated flow model has been formulated and the computer program written. This submodel is operational on a stand-alone basis. It includes provision for evapotranspiration, and is capable of completely solving the water movement in individual prismatic elements. An available distributed kinematic overland flow model is being utilized in the initial model.

A modified U. S. Geological Survey three-dimensional ground-water flow model is used to simulate flow in the multiaquifer watersheds. In the C06 and M09 models, each layer of nodes represents an aquifer. Input to each simulation includes: ground-water recharge rate, aquifer hydraulic conductivity, confining bed leakance, and stream and spring coefficients.

I. STUDY OBJECTIVES

Increasing energy demands are likely to necessitate additional coal production. It is expected that much of this increased demand will be satisfied through increased production from surface operations. As a consequence there will be an increased need for basic information on mining and reclamation including both environmental and economic considerations.

In Appalachia, land is being disturbed by surface mining at an accelerating rate to obtain coal for electric power production and other uses. Such mining may have profound effects on runoff, erosion, and water quality in a watershed.

Strip mining may bring changes in the hydrology of surface mined areas in two interrelated phenomena: flooding and sediment transport. Barren spoil areas and decreased infiltration rates tend to increase peak flow rates of runoff from mined areas. Such increased runoff erodes the spoil areas and carries spoil particles that cause sedimentation of waterways and reservoirs. Until spoil areas become stabilized with vegetation, significant quantities of sediment will continue to be transported.

A wide range of new hydrologic information is required to assess the erosion and sedimentation potential for different materials and vegetative covers, the design of sediment dams, and soil-water flux to estimate the acidity of drainage water. In addition, the effects of surface mining on the hydrologic regime need to be established for a full determination of the quantity and wuality of runoff from watersheds before and after mining. Information is also needed to meet the pressing need to determine acceptable slopes and slope lengths to minimize erosion.

The motivation for the study was the federal surface mining reclamation legislation passed by the 94th Congress which was later enacted by the 95th Congress as Public Law 95-87, "Surface Mining Control and Reclamation Act of 1977." The Federal Energy Administration (FEA) and the U.S. Bureau of Mines outlined some basic study needs for obtaining desired hydrologic and water quality data from watersheds subjected to surface mining through the three phases: (1) Pre-mining, (2) Mining, and (3) Post-mining. Methods or procedures were also desired for use in answering the broader questions of how surface mining influence hydrology and water quality, and what would be the most economic and environmental impacts of a more comprehensive regulation of surface mining and reclamation.

The specific objectives of the study were broken down into tasks for which the U.S. Department of Agriculture - Science and Administration - Agricultural Research (USDA-SEA-AR) and the Ohio Agricultural Research and Development Center (OARDC) were responsible, with designated contributions by both the U.S. Geological Survey (USGS) and the Soil Conservation Service (SCS) who agreed to accomplish certain tasks under reimbursable agreements with USDA-SEA-AR. The objectives are as follows:

1. Obtain and analyze for four years with one year of data obtained prior to surface mining, hydrologic and water quality data from four treatment watersheds, 30 to 60 acres in size, scheduled for mining of different coal seams. Obtain and analyze hydrologic and water quality data from erosion and treatment plots for two to three years and a control watershed for four years.

2. Characterize the study watershed and plots, and obtain physical and chemical data for the soils and overburden materials prior to surface mining and for the replaced topsoil and underlying spoil material following surface mining.

3. Describe the hydrogeology of the watersheds and the water quality characteristics of the aquifer systems for pre-mining and post-surface mining conditions, and develop or adapt a ground-water model for simulations of the ground-water flow conditions and movement of solutes for the pre- and post-surface mining conditions.

4. Develop or modify a computer model for simulation of the hydrologic and water quality regimes of the study watersheds for both pre- and post-surface mined conditions, by incorporating mathematical representations of separate models for the water flow components and sediment and chemical transport, with emphasis on selection of model parameters that can be reasonably acquired for nonstudy areas within the physiographic region for application of the model.

5. Determine costs to obtain the necessary physical, chemical, and hydrologic data, including legal and administrative costs, as required for surface mining permits as well as costs for obtaining these data at alternative degrees of accuracy and completeness; and determine costs and benefits of alternative degrees of control of runoff, sediment and water quality.

II. EXPERIMENTAL DESIGN AND PROCEDURES

A. Introduction

A total of five watersheds, ranging in size from 29 to 52 acres, were selected to study the effects of mining and reclamation on hydrology and water quality. Four of these watersheds will be mined, and one will be left in its natural state and used as a control watershed. All the watersheds are located in the east-central part of Ohio, as shown in Figure 1, and are numbered in accordance with surface mineable coal seams. The study watersheds in Coshocton County (C06 and A06) and the one in Muskingum County (M09) are located in the Muskingum River Basin. The two Jefferson County Sites (J11 and J08) drain into small tributaries of the Ohio River. Maps of watersheds C06, M09, J11, J08 and A06 are shown in Figures 2 through 6, respectively.

The four watersheds to be mined, each with a different coal seam, were chosen because the natural and mine-modified geologic profiles would be different, reflecting different groundwater flow regimes, soils, and vegetation--all major factors to consider in the overall hydrology of any watershed. The watershed to be used as a control to reflect only the natural climatic factors has a record of hydrologic data and an outcropping coal seam (Figure 6).

In order to adequately evaluate the hydrology of watersheds, weather and surface and subsurface hydrologic data must be collected. Data required are those that can be used to numerically describe the components of the hydrologic cycle, either directly or indirectly. Also, for modeling of watershed hydrology and water quality, spatial and temporal numerical descriptions of the components are necessary. The hydrologic data collection system for each watershed was designed to meet these needs.

The watersheds to experience surface mining of a different coal seam are to be studied in their natural condition and through the mining and reclamation phases, in order to investigate the effect of surface mining on hydrology and water quality. The pre-mining phase was to last approximately one year, but a one-year period is too short to show how an individual watershed responds to varying weather conditions (i.e., dry years, wet years, extreme events, etc.). To overcome this, data from each study watershed and the control watershed with a long hydrologic record, will be utilized to develop (or adapt) a hydrologic model that describes and predicts the hydrologic behavior of each study watershed under varying inputs.

Because of the five-year limit for the project, it was necessary to restrict either the pre-mining or post-mining phase; the mining phase would take an estimated 8 to 12 months. The decision was made to restrict the pre-mining phase so that the post-mining phase could be as long as possible to study the hydrologic and water quality responses to mining and reclamation.

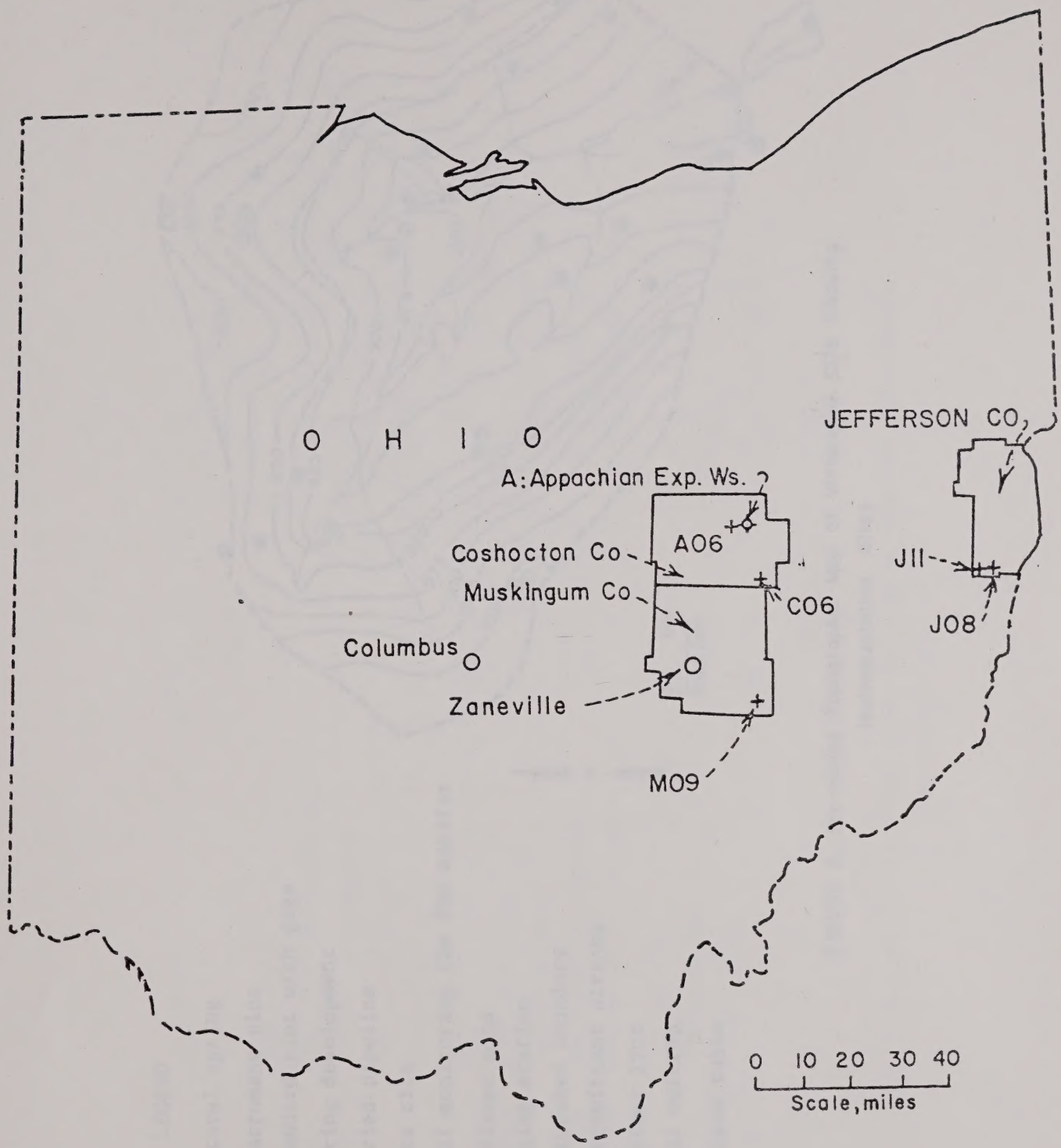


FIGURE 1.- Location of Study Sites

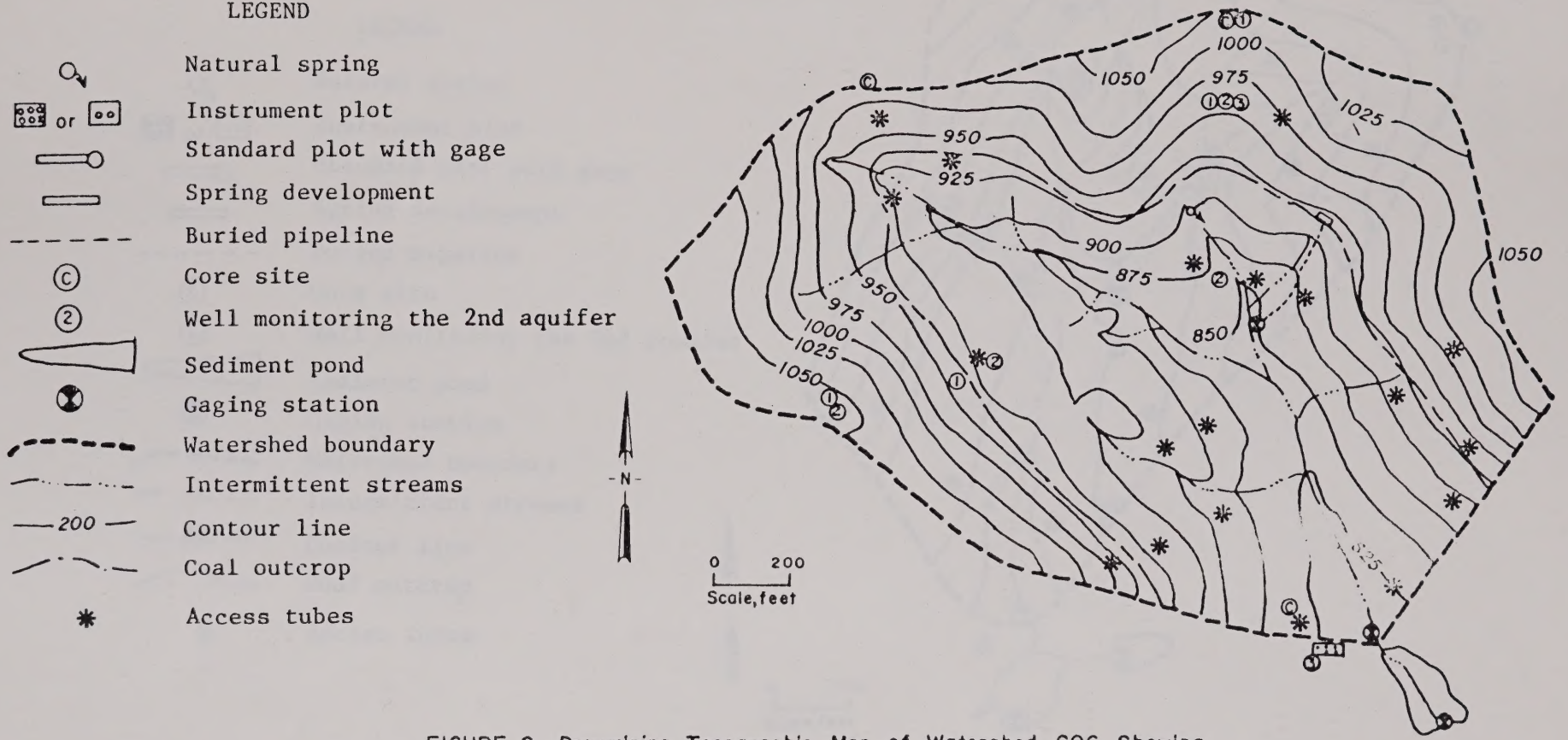


FIGURE 2.-Pre-mining Topographic Map of Watershed CO6 Showing Instrumentation Sites

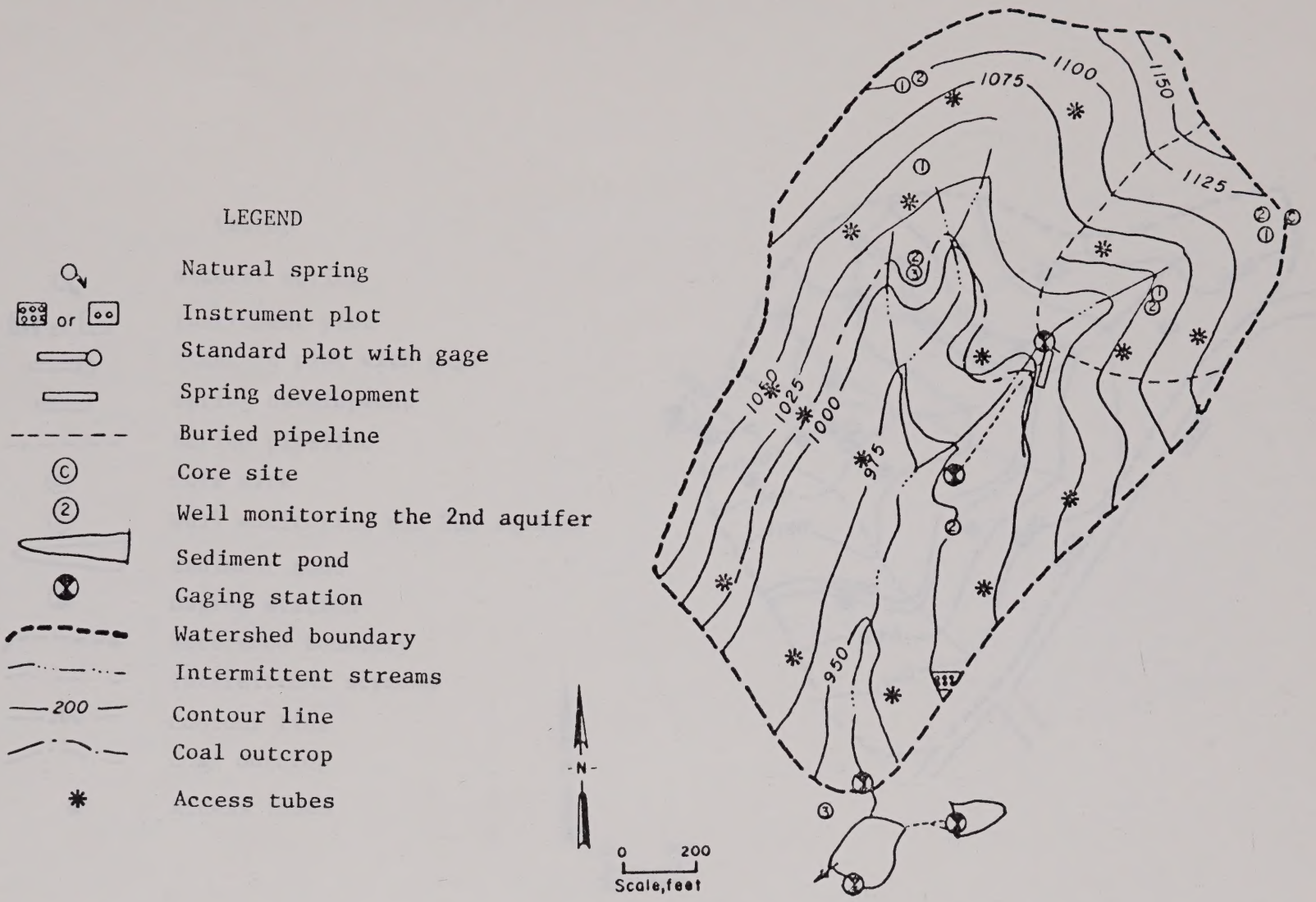


FIGURE 3.- Pre-mining Topographic Map of Watershed MO9 Showing Instrumentation Sites

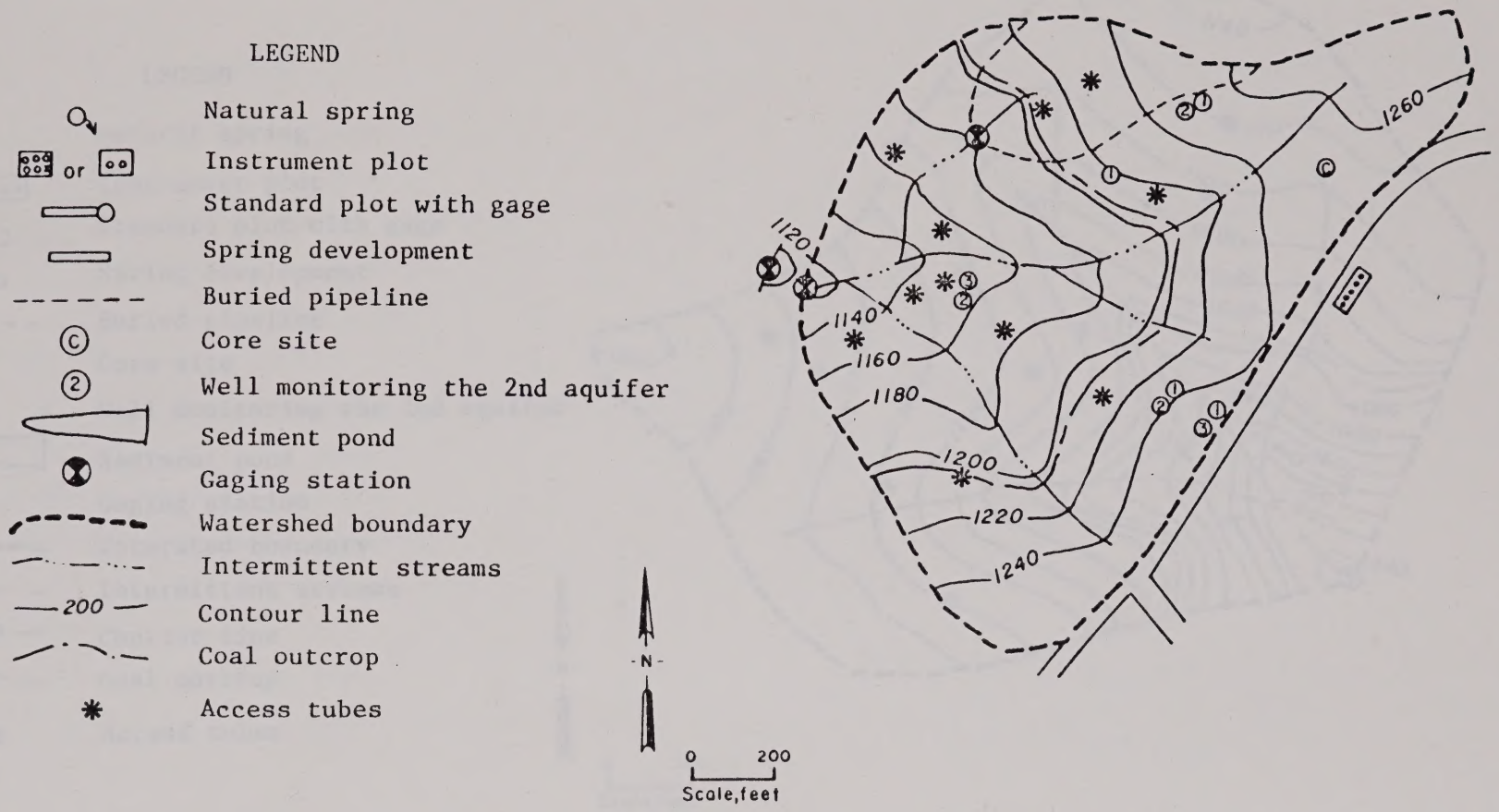


FIGURE 4.- Pre-mining Topographic Map of Watershed J11 Showing Instrumentation Sites

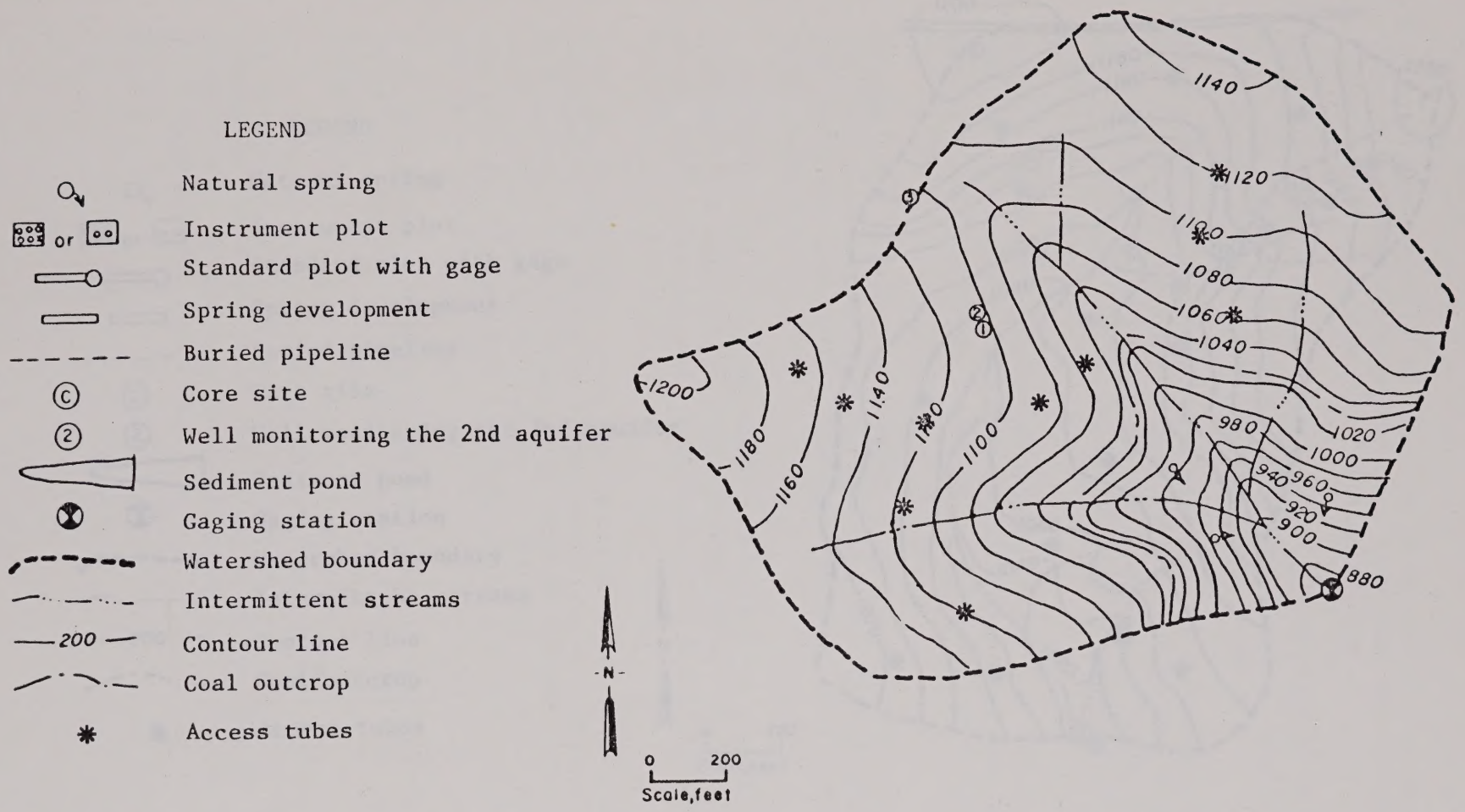


FIGURE 5.- Pre-mining Topographic Map of Watershed JO8 Showing Proposed and Existing Instrumentation Sites

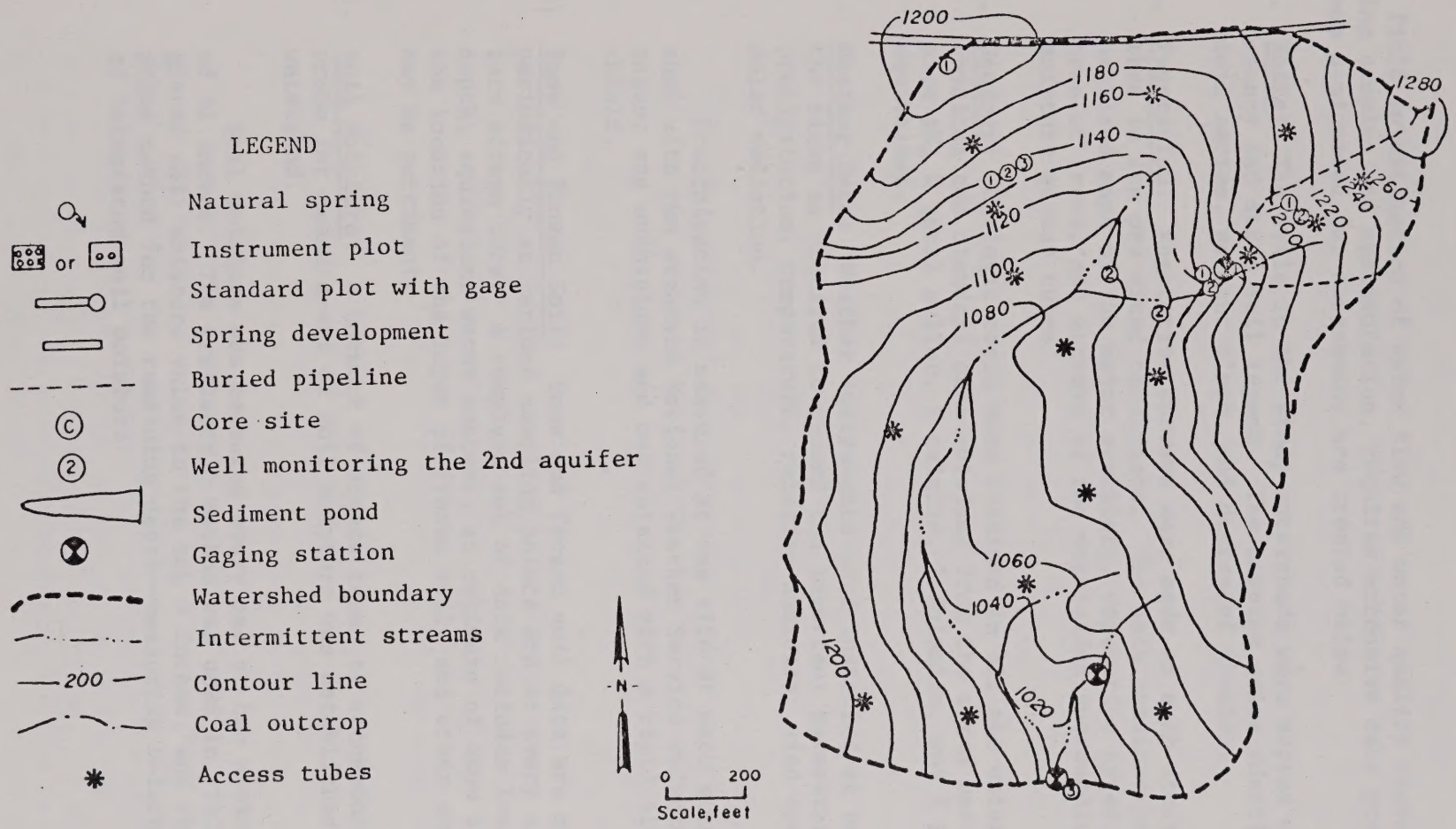


FIGURE 6.–Pre-mining Topographic Map of Watershed A06 Showing Instrumentation Sites

B. Investigational Components

A field investigation of water flow and water quality components, including erosion and sedimentation, requires extensive data procurement. The tiems designated for assessment are treated below:

1. Soils: The soils in the study watersheds were mapped using a county and state soil legend. The mapping units identify the soil series, percent slope, and degree of erosion.

2. Vegetation: Vegetative surveys were made on each study watershed in its pre-mined conditions. The data obtained were generalized maps of the major overstory, vegetation types, basal area of trees, and surveys of the vegetation surrounding soil moisture access tubes.

3. Geology: Geologic cores were obtained in all the watersheds. Physical and chemical data obtained from the cores were particle size pH, % total sulfur, % calcite, % dolemite, and % $CaCO_3$ equivalent.

4. Weather Data: Weather instruments were installed at each of the sites as required to record the important parameters of precipitation, temperature, relative humidity, wind speed, and solar radiation.

   Precipitation is measured at one site at each study watershed with two standard National Weather Service weighing bucket gages; one unshielded and one shielded with a rigid Alter type shield.

5. Snow and Frozen Soil: Snow and frozen soil data are collected periodically at various sampling points and at every soil moisture access tube. A complete set of data includes location, snow depth, equivalent water content, an estimate of snow distribution, the location of the layer of frozen soil, and other comments that may be pertinent.

6. Soil Moisture: A network of access tubes to accommodate a neutron probe for measurement of soil moisture was established in each watershed.

   Soil moisture was measured every one or two weeks to a depth of 51 inches. The gravimetric method was used to yield an integrated soil moisture value in the top 9 inches, and the neutron probe method for the remaining depth--measuring 6-inch increments of integrated soil moisture.

7. Infiltration: A portable rainfall simulator-infiltrometer was used to study infiltration. The 6 feet by 6 feet infiltrometer has the capacity of applying water at rates from 0.1 to 8.0 inches per hour measured by flow meters for each of the six - 2 feet by 3 feet modules. Water-drop sizes are controlled by the velocity of air flowing through orifices (three inches on center) in which the capillary needles are placed. Mean-drop size diameter of natural rainfall can be duplicated for intensities up to 4 inches per hours. With the flow modules suspended at a height of 8 feet, the kinetic energy of the simulated rainfall is about 85 percent of natural rainfall.

   To collect surface runoff, a three-sided metal frame is driven to a depth of 8 to 12 inches into the soil. On the open downslope side, a wooden cut-off (the top edge shaped to conform with the surface) is placed at an equal depth into the ground and a runoff collector attached. Runoff is transferred from the attached collector trough to a tank by a vacuum system and measured with a water stage recorder.

8. Spring Discharge: Springs situated on the outcrop of the study coal seams in Watersheds C06 and M09 were developed to measure discharge and collect water quality samples. A trench was dug to the coal underclay and a 3-inch Polyvinal Chloride (PVC) pipe installed. Then the trench was partially backfilled with gravel, and finally backfilled with the original soil. Since the land surface at the outcrop was to be disturbed, the water was conveyed downslope by PVC pipe beyond the estimated toe of the spoil bank and measured in a protected and coated 0.75-foot HS-flume. The A06 site had an existing spring developed on the Clarion clay, which is the second highest impermeable layer in the watershed.

9. Surface Water Hydrology and Quality: In addition to the five principal watersheds to be used to monitor hydrology and water quality, three small subwatersheds for measuring runoff were put into operation. Each of these small watersheds, 2.2 to 7.0 acres in size, is located in separate study watersheds.

   The runoff data were collected by use of four types of measuring devices: H-flumes, drop-box weirs, a broad-crested V-notch weir, and a Parshall flume. Locations of the surface runoff measuring devices are shown in Figures 2-6.

   Installation of all weirs was basically the same; a trench was dug perpendicular to the stream channel to a relatively impervious layer and a concrete footing and cut-off wall poured. The cut-off wall was designed with an opening for attaching the flow measuring device and an extension to both sides to decrease the hydraulic gradient of unmeasured underflow. In addition, an energy dissipating pad with roughness elements was constructed at the larger weir installations.

The C06, M09, and A06 outlet sites were instrumented with Coshocton vane type, automatic water quality (composit samplers. The sampler is a rotating, tear-shaped vane that passes under a constant discharge outfall moved by the stilling well float.

The water stage or gage height was obtained at each weir installation by use of a float-operated recorder. Breakpoint data are extracted from the recorder traces and the discharge obtained by the use of stage-discharge relationships.

Installation of Chickasha samplers at the C06 and M09 sites was for obtaining discrete samples at time intervals throughout the hydrograph for sediment and particle size determinations. Grab samples are also obtained at all sites for these purposes.

Surface water samples (base flow and runoff) from four of the watersheds (C06, M09, J11 and A06) were obtained for determinations of various water quality parameters (Appendix A). The frequency of sampling varied from watershed to watershed, depending upon the number of runoff events. The goal was to obtain 10 storm samples and seasonal base flow samples. All the parameters were determined in the laboratory except for color, specific conductance, pH, and temperature which were determined in the field.

The procedures used for determination of the various water quality parameters were as follows: Standard Methods for acidity, alkalinity, bicarbonate, carbon dioxide, chloride, color, hardness, nitrate, pH, phenol, sulfate, suspended solids, and dissolved solids; inductively Coupled Argon Plasma Method for aluminum, antimony, barium, cadmium, calcium, copper, iron, lead magnesium, manganese, nickel, phosphorus, silver, sodium, strontium and zinc; Electrod Method for ammonia, cyanide, fluoride and hydrogen sulfide; Atomic Absorption for arsenic (graphite rod) and mercury (flameless); Diphenylcarbazide Method for hexavalent chromimum; and Fluorometric Method for selenium.

In addition to runoff and base flow samples, monthly precipitation samples from M09 and J11 sites were obtained and analyzed for various parameters (see Appendix A).

Since the quantities of sediment collected for each runoff or base flow event at a given site were too small for the complete analyses, the sediment samples obtained from each site from different events were combined until sufficient quantities were collected from a given site for chemical analyses.

10. Ground-Water Hydrology and Quality: Descriptions of the geology and ground-water conditions are based mainly on subsurface data. Continuous coring provided stratigraphic definition of each watershed. A single core was obtained near the divide of each watershed, except at C06, where cores from three locations were used to construct the stratigraphic column.

Observation well networks were established in each watershed. The wells were drilled by the air-rotary method and each was cased (6-inch diameter) so as to be open to only one of three major saturated zones. Most wells were completed in one of the top two zones.

Gamma and electric logs were made of most wells and core holes, and caliper and neutron logs were made of selected wells.

Water levels were measured monthly in all wells and recorded hourly in selected wells during part of the pre-mining period.

Aquifer tests (pumping and slug tests) to determine hydrological properties were made at M09 and A06. Mining took place before any tests were made at C06, and many of the wells at M09 were destroyed by mining before testing began. Pumping rates (about 0.5 gallon per minute) and duration of pumping (1-2 hours) was limited by the very low water-yielding capability of the rocks. In many wells the available head was too low to warrant test pumping. Slug tests were made at some of the wells by injecting 8-10 gallons of water and measuring the rate of decline of the water level.

Water samples were collected on a quarterly basis from wells and springs for determination of various water quality parameters (see Appendix A).

Early methods of sample collection were inconsistent because of problems in obtaining representative samples from wells. Later use of a small gas-operated membrane pump decreased the discharge to a rate which could be more easily supplied by the wells. The wells were pumped about 5 minutes, allowed to recover, then pumped again to collect the sample. Temperature, specific conductance, pH, and alkalinity were determined in the field. Samples were kept chilled until laboratory determinations of the remaining parameters were made.

Reference in this report to recommend limits of concentration are based on drinking-water standards (1977) of the U.S. Environmental Protection Agency.

11. Erosion and Treatment Plots: Three sets of erosion and treatment plots are to be installed on different slopes and with different lengths on the slopes; one set on each of the distrubed overburdens associated with the Number 6, 9, and 11 coals. The erosion plots will consist of graded spoil material with a veneer of topsoil to the depth required by current regulations except for one plot on each slope which will have the original spoil exposed. The treatment plots (10 at each site) will consist of standard plots (72.6 ft. by 15 ft.) on a 9 percent slope, with treatments of differeing depths of topsoil and different mulching rates.

The erosion and treatment plots have been located on appropriate slopes outside the boundaries, but near watersheds C06, M09, and J11. Construction has been initiated on the C06 plots.

The data from the plots will be used to develop criteria for diversion spacing, erodibility factors for soil prediction equations, and an erosion model for surface mined land.

12. Sediment Ponds: Sediment ponds, which are constructed before mining, are instrumented to monitor both inflow and outflow water quality and quantity. The outflow of the ponds will be instrumented with an H-flume for quanity and a Coshocton wheel sampler to obtain samples for water quality determinations.

III. COMPOSITE MODEL APPROACH

The hydrologic model will consist of several separate component models which will be linked together to provide a composite model for simulation of the hydrology within and on the watershed. These separate models are:

1. Ground-Water Model: This model will be a modification of the model developed by the USGS ("Finite-difference model for simulation of three-dimensional groundwater flow"). In operation it will receive input (percolation) from the Unsaturated Flow Model (see item 2), and will supply the water table levels to define the lower boundary of the unsaturated model as well as provide seepage effluent to the Overland Flow Model (see item 3).

2. Unsaturated Flow Model: This model will account for the water movement in the unsaturated condition between the ground surface and the water table. To increase computation efficiency, this unsaturated model will be based on the one-dimensional flow equation and provide a complete solution of the water movement in the upper zones. In order to accommodate the watershed, which is three-dimensional, the one-dimensional vertical flow solution will be obtained for each prismatic element within the watershed, or solutions at some of these prismatic elements will be obtained by interpolation from one-dimensional solutions covering the range of depths and conditions in existence.

3. Overland Flow Model: This model will numerically solve the kinematic wave equations, to describe the manner in which precipitation excess and ground-water effluent flows down the watershed's surface into the streams. The tractive forces from the velocity of this overland flow will be important in determining surface erosion. The overland flow model will likely be based on computer programs currently in existence which describe the watershed surface by a cascade (logical flow sequence) of overland flow plans and channels.

4. Evapotranspiration Model: The evapotranspiration model will account for water removal by plant transpiration and surface evaporation. In practice it will be very closely associated with the unsaturated flow model and might be considered part of that model rather than a separate model. It will consist of equations which determine the rate of evapotranspiration as a function of roots penetration, meterological elements, species of plants, stage of plant growth, and a soil water parameter.

The separate component models will be coupled to perform as a composite model and each will be based on fundamentally sound formulations. Where partial differential equations are involved, the associated initial boundary value problems will be solved numerically because the nonlinear nature of the equations prevent closed form solutions from being obtained.

The time increment that can be used in numerically solving the differential equations for this unsaturated flow model will be larger, no doubt, than the time increment needed for the overland flow model, but shorter than the time increment of the ground-water model. The depth of each prismatic element of unsaturated flow will equal the difference in watershed surface elevation at that point and the ground-water table at that point. Thus, the heights of individual unsaturated prismatic elements will depend upon the solution from the ground-water model. In turn, the flow through the unsaturated zone or recharge data is needed by the ground-water model for its solution. Likewise, the overland flow model will require data from both the unsaturated and ground-water models. As input for each new time step, this needed information will be passed between the separate component models.

The techniques for coupling the ground-water and unsaturated model will pass the needed information back and forth after individual time steps have been completed and not during the individual solutions of a time step. Thus, it is possible, for example, for the unsaturated model to use a smaller time increment than the ground-water model. Likewise, data will be passed back and forth to the overland flow model at the completion of individual time increments. The time increment of the overland flow model might also be independent of the other time increments.

The heart of the composite model will be the program to couple the separate models and direct and coordinate their separate activities so that complete and accurate simulations of the total watershed is achieved.

IV. RESULTS OF BASE LINE INVESTIGATIONS

A. Introduction

The periods of pre-mining record for each watershed, and for each parameter for a watershed, varied as instruments were installed and mining progressed. The pre-mining records for C06 and M09 cover less than one year. The end of the pre-mining phase occurred when the watershed hydrology was changed by tree removal and road building prior to mining. The J11 site has not yet been mined, and the A06 control site will not be mined, but an arbitrary cutoff date of December 31, 1977 was made for all the pre-mining data included in the Phase I report. Pre-mining data after this date will be presented in a supplemental report. Because J08 has not been completely instrumented, the pre-mining period for this has not begun, except for collection of some ground-water data. Data on air temperature, relative humidity, wind, and solar and net radiation collected at the J11 site, however, can be extrapolated to J08, since they are only about 5 miles apart and variations over short distances are expected to be minimal for these parameters. The parameters which were analyzed from the surface water, precipitation, and groundwater samples are listed in Appendix A.

B. Watershed Investigations

1. Watershed C06

The pre-mining condition of the watershed is characterized by an ephemeral stream of 2000 feet in length. The maximum elevation is 1075 feet and the minimum elevation is 930 feet. The watershed has an area of 52 acres, with a southeast aspect.

A total of eight soil types, constituting 26 soil delineations, were mapped in the watershed. Five of the most extensive and representative soils - Johnsburg, Gilpin, Dekalb, Coshocton, and Monogahela - were sampled and complete description and characterization data obtained. In general, these soils have favorable rooting depths and medium to high water holding capacities. Most of the soils analyzed, with exception of the Dekalb, would provide good material for topsoiling.

The vegetation on the watershed consisted mainly of deciduous trees. The site had poor species composition and growing conditions. Major species are aspen, dogwood, black cherry, maple, red oak and musclewood. Ground cover was also quite variable. Average ground cover values for herbs, woody vegetation, duff, and bare soil and/or rock are 32, 14, 38 and 16 percent, respectively.

The precipitation record spanning the C06 watershed pre-mining period was from December 6, 1975 through November 3, 1976. The total precipitation for the period of record was 40.37 inches, with snowfall accounting for 2.79 inches. The most extreme event during the pre-mining phase occurred on July 8, 1976 when the rainfall totaled 1.65 inches. The peak intensity of this event was 5.16 in/hr for 5 minutes - totaling 0.43 inches. The highest

2-hour intensity of 1.60 in/hr during this event, was approximately a 5-year precipitation event.

Infiltration tests were run on the watershed on the Coshocton, Gilpin, and Dekalb soils. At application rates of 2.0 and 2.5 inches per hour, equilibrium rates of 0.56 and 1.25 inches per hour were reached in about 3 and 4 hours for the Coshocton and Gilpin soils, respectively. The data for the Dekalb is considered questionable.

A spring was developed on the watershed at the coal outcrop. The minimum flow was 0.003 cubic feet per second (cfs) and the maximum was 0.012 cfs. The spring's range of average daily flow was 0.003 to 0.0052 cfs.

Mining commenced on watershed C06 before a full year of water quantity and quality data were obtained (data for the fall are missing). The total surface flow for the period of record (1-1-76 to 11-3-76) was 33.54 inches. The peak event of 5.86 cfs occurred on July 8, 1976 with the causative precipitation being 2.39 inches.

Base flow water had average concentrations of iron, manganese, and suspended solids, for an average flow rate of .44 cfs, of 183 µg/1, 102 µg/1, and 247 mg/1, respectively. The runoff water had average concentrations of iron, manganese, and suspended solids, for an average flow rate of 2.13 cfs, of 209 µg/1, 97 µg/1, and 870 mg/1, respectively.

Ground-water levels indicate that the ground-water divide for both the top and middle aquifers at C06 coincide with the surface drainage divide. The top aquifer is above the clay that underlies the No. 6 coal. The middle aquifer is above the clay that underlies the No. 4 coal. Water in the deep aquifer moves northward; the top of this saturated zone is 30-100 feet below the middle aquifer.

Water in the top aquifer is mostly of the calcium bicarbonate type. Specific-conductance values indicate that dissolved-solids concentration in parts of the middle and deep aquifers exceed the recommended limit of 500 mg/1. Concentrations of dissolved iron and maganese commonly exceeded the recommended limits of 0.3 and 0.05 mg/1, respectively. Concentration of dissolved cyanide exceeded the recommended limit (0.01 mg/1) in one sample.

2. Watershed M09

The pre-mining conditions of watershed M09 are characterized by a continuous flowing stream of 1800 feet in length. The maximum elevation of the watershed is 1165 feet and the minimum elevation is 933 feet. The watershed has an area of 43.5 acres with a south-southeast aspect.

A total of 14 soil types, constituting 33 soil delineations, were mapped in the watershed. Five of the most extensive and representative soils -- Lowell, Upshure, Wellston, Tilsit, and Brookside -- were sampled and complete description and characterization data obtained. In general, these soils have a high available moisture holding capacity. The texture, cation exchange capacity, and base status make these soils well suited for plant

growth, except where there is a high clay content near the surface. With the exception of the Upshur mapping unit and other areas where high clay contents are found near the surface, the soils of the watershed would be very good for top soiling.

The vegetation on the watershed consisted mainly of pasture species. Woody species occurring on the site included sycamore, tulip poplar, elm, red maple, red oak, white oak, and dogwood. Approximately 77 percent of the ground area was covered with a mixture of grasses and broadleaf herbs, 8 percent with woody vegetation and the remaining 15 percent was bare and/or covered with organic matter.

The precipitation record spanning the M09 watershed pre-mining period was from May 1, 1976 through January 19, 1977. The total precipitation for the period was 24.02 inches with snowfall accounting for 2.93 inches. The most extreme event occurred on July 11, 1976 when rainfall amounted to 3.02 inches. The peak intensity of this event was 3.60 in/hr for three minutes -- totaling 0.18 inches. The frequency associated with the event was a 25-year, 3-hour event of 2.73 inches.

A spring was developed on the watershed at the outcrop of the No. 9 coal seam. The minimum flow rate of the spring was 0.0 cfs and the maximum was 0.214 cfs. The average daily springflow ranged from 0.0 cfs to 0.0444 cfs.

Mining commenced on the watershed before a full year of water quantity and quality data were obtained (data for the winter and early spring are missing). The total flow for the period of record (6-8-76 to 1-19-77) was 12.44 inches, while the total precipitation for the same period was 20.21 inches. The peak runoff event occurred on July 11, 1976. The peak flow for the event was 81.95 cfs with the causative precipitation being 3.02 inches.

Base flow water had average concentrations of iron, manganese and suspended solids, for an average flow of 0.024 cfs, of 46 µg/1, 24 µg/1, and 157 mg/1, respectively. Runoff water had average concentrations of iron, manganese and suspended solids, for an average flow rate of 2.711 cfs, of 228 µg/1, 92 µg/1 and 1110 mg/1, respectively.

Three aquifer systems were measured in Watershed M09. The ground-water divide for the top aquifer (above the clay that underlies the No. 9 coal) coincides with the surface drainage divide. Flow in the middle aquifer (above the clay that underlies the No. 8 coal) involves an unmeasured west-to-east underflow across the northern part of the watershed. This aquifer is part of a more extensive flow system which away from the influence of the stream and is recharged and discharged mostly outside of the watershed. Potentiometric head in the northwest part of the middle aquifer is above the overlaying clay, at least during part of the year, so that confined conditions exist. In the deep aquifer, water movement is northerly; the top of this saturated zone is about 70 feet below the middle aquifer.

Dissolved solids concentration of much of the water in the middle and deep aquifers exceeds the recommeded 500 mg/l limit. Chloride concentration in excessive (greater than 250 mg/l) in the eastern part of the middle aquifer and in the deep aquifer. Water in the top aquifer is very hard (greater than 180 mg/l hardness as $CaCO_3$). It is softer in parts of the deeper aquifers where sodium is the dominant cation. Dissolved iron exceeded the recommended limit (0.3 mg/l) in one sample, and dissolved manganese was excessive (greater than 0.05 mg/l) in several samples. The recommended limit for dissolved cyanide concentration (0.01 mg/l) was exceeded in two samples from the middle aquifer and two from the deep aquifer.

3. Watershed J11

The pre-mining condition of Watershed J11 is characterized by an emphemeral stream of 1400 feet in length. The maximum elevation of the watershed is 1280 feet and the minimum elevation is 1135 feet. The watershed has an area of 29.1 acres, with a western aspect.

A total of four soil types, constituing 10 soil delineations, were mapped in the watershed. The soil mapping units are the Berks, Coshocton, Culleka, and the Gilpin. Soil sampling has not been completed as yet for this watershed.

Much of the area is in pasture, both open and wooded. Only 4 of 11 sample points are wooded and average timber volumes are low. The dominant species are black cherry, ash and ailanthus. Ground cover for the area is quite variable, including herbaceous vegetaion ranging from 40 to 100 percent, woody vegetation 0 to 9 percent, duff cover 0 to 55 percent, and bare soil and/or rock form 0 to 14 percent. Average ground cover values for herbs, woody vegetation, duff and bare soil are 87,2, 10 and 1 percent respectively.

The precipitation record for the J11 watershed began on May 1, 1977. Since the watershed has not yet been mined, the report was arbitrarily cut off at December 31, 1977. The toal precipitation for the period was 28.64 inches. The largest event during the period occured on July 21, 1976 when rainfall amounted to 1.93 inches. This event was a 2 year, 3-hour event of 1.66 inches. The peak intensity of this storm was 7.5 in/hr for 2 minutes, totaling 0.25 inch.

The total flow for the period of record was 2.07 inches while the total precipitation was 27.14 inches. The peak event occurred on July 21, 1977. The peak flow for the event was 6.31 cfs, with the causative precipitation being 1.93 inches. Baseflow water had average concentrations of iron, manganese, and suspended solids, for an average flow rate of .042 cfs, of <3 µg/l, 25 µg/l, and 44 mg/l respectively. The runoff water had average concentrations of iron, manganese and suspended solids,for an average flow of 0.89 cfs, of 14 µg/l, 54 µg/l. and 118 mg/l, respectively.

The top aquifer at the J11 site is above the shaly clay that underlies the No. 11 coal; the middle aquifer occurs above the shaly clay that underlies the No. 9 coal. Underflow does not appear significant in either aquifer.

The top aquifer discharges to the surface as evapotranspiration and at one ungaged spring; the middle aquifer discharges as evapotranspiration and base flow. The two deepest wells penetrate mined-out openings in No. 8 coal and are dry; much of the No. 8 coal has been removed. More detailed description of the J11 ground-water system will be undertaken as pre-mining data collection continued.

The top aquifer at J11 contains water of the calcium bicarbonate and calcium sulfate types. Samples collected from the middle aquifer were bicarbonate waters, and sodium and calcium were the dominant cations. The predominance of one major ion over another is not as extreme at J11 as at other study watersheds.

4. Watershed J08

The pre-mining conditions of Watershed J08 are characterized by a continuous flowing stream of 1200 feet in length. The maximum elevation of the watershed is 1200 feet and the minimum elevation is 880 feet. The watershed has an area of 51.8 acres, with a southern aspect.

A total of four soil types, constituting 13 soil delineations were mapped on the watershed. The soil mapping units are the Elba, Gilpin, Guernsey, and surface mine spoil. Soil sampling has not been completed as yet for the watershed.

On this watershed herbaceous vegetation cover ranges from 6-63 percent, woody cover from 0-5 percent, duff cover from 0-77 percent, and bare soil and rock 0-82 percent. The average cover values for herbs, woody vegetation, duff, and bare soil and/or rock are 35, 4, 42 and 19 percent respectively. The gross sawtimber volume is 389 board feet per acre and the major species are black locust, black cherry, American elm, osage orange, and black walnut. Major poletimber species, representing a gross of 7.8 cords per acre, are black cherry, osage orange, black locust, and white ash. Woody reproduction species includes white ash, cherry, black locust, oak, osage orange, and elm.

Weather data collected for the J11 site are being used for this site also. No surface water quality or quantity data are available since measuring and sampling equipment are yet to be installed.

Definition of the flow systems is not possible because only one well was completed in each aquifer.

Analyses of ground water from J08 indicate calcium sulfate water in the top aquifer, sodium bicarbonate water in the middle aquifer, and sodium chloride water in the deep aquifer. Water in the top aquifer is very hard, has dissolved-solids concentration exceeding the recommended limit of 500mg/1, and sulfate concentration exceeding the recommended limit of 250 mg/1. Water in the middle aquifer is much softer, but slightly brackish and contains chloride concentrations exceeding the recommended limit of 250 mg/1. Water in the deep aquifer is highly brackish.

5. Watershed A06

This watershed is the control site and will not be mined. The watershed is characterized by a continuous stream of 1750 feet in length. The maximum elevation of the watershed is 1290 feet and the minimum elevation is 1008 feet. The watershed has an area of 43.6 acres, with a southern aspect.

A total of four soil types, constituting 10 soil delineations, were mapped in the watershed. The soil mapping units are the Berks, Coshocton-Rayne complex, Dekalb, and Rayne.

Vegetation is quite diverse, ranging from upland oak-hickory types to planted stands of white and red pine. Vegetation within the area is of a discontinuous cover form. Small areas within the watershed show recent interruptions. Ground cover is quite variable, including herbaceous vegetation ranging from 2 to 56 percent, woody vegetation from 1 to 42 percent, and duff cover from 38 to 86 percent. The average cover values for herbs woody, duff and bare are 3, 16, 68 and 3 percent respectively. The gross sawtimber volume is about 18,000 board feet per acre and the major species are tulip poplar, red oak, white oak, red pine and white pine. Poletimber gross volume is 27.0 cords per acre and the major species include red pine, tulip poplar and black locust.

The precipitation record considered for this report covers the period from July 1, 1976 through December 31, 1977. The total precipitation for the period of record was 95.32 inches. The most extreme event occurred on July 11, 1976 when the rainfall amounted to 1.75 inches. This event was a 5-year, 1-hour event with 1.61 inches falling in one hour.

Springflow was measured from an existing developed spring on the Clarion clay, which comprises the second highest impermeable layer in the watershed. The minimum flow rate of the spring was 0.0003 cfs and the maximum was 0.0712 cfs. The average daily springflow ranged from 0.0003 cfs to 0.444 cfs.

The total surface water flow for the period amounted to 33.95 inches. The peak runoff event occurred on July 11, 1976. The flow for the event was 13.80 cfs, with the causative precipitation being 1.75 inches. Base flow water had average concentrations of iron, manganese and suspended solids, for an average flow of .0098 cfs, of 22 µg/1, 344 µg/1 and 45 mg/1, respectively. The runoff water had average concentrations of iron, manganese, and suspended solids, for an average flow rate of 0.84 cfs, of 52 µg/1, 64 µg/1, and 147 mg/1, respectively.

The top aquifer at the A06 site occurs above the clay that underlies the No. 6 coal; the middle aquifer occurs above the clay that underlies the No. 4 coal. Surface discharge from the top aquifer is mainly as evapotranspiration; that from the middle aquifer is evapotranspiration, base flow to the stream, and spring flow at spring gage site. Underflow out of the watershed to the northwest occurs in both aquifers, although flow is from the divide toward the coal outcrop at times in the top aquifer. In

the deep aquifer water moves southward; the top of this saturated zone is about 20 feet below the middle aquifer.

Ground water in the top aquifer of the control watershed is of the calcium bicarbonate type. As in the other watersheds, water types in deeper aquifers are more diverse. In the middle aquifer, calcium of sodium and sulfate or bicarbonate may each predominate. The deep aquifer contains sodium bicarbonate and sodium sulfate waters. Dissolved-solids concentration exceeded 500 mg/l in two samples from the middle aquifer and from both wells in the deep aquifer. Most water is hard to very hard. Recommended limits (EPA) of concentration for dissolved iron and manganese (0.3 and 0.05 mg/l, respectively) were commonly exceeded in all aquifers. Cyanide concentration exceeded 0.01 mg/l in one sample.

C. Hydrologic Modeling

Investigations were conducted on several aspects of the composite hydrologic model components, as briefly discussed below:

1. Ground-water Model

Ground-water modeling efforts thus far have been for pre-mining flow conditions for Watersheds C06 and M09. The U. S. Geological Survey model used employs a finite-difference numerical algorithm to arrive at approximate solutions to the partial differential equations that describe ground-water flow. The option used has three layers with each layer corresponding to an aquifer which consists of an array of approximately 25 x 17 nodes; each node representing an area of 100 feet by 100 feet. The model is quasi-three-dimensional in that vertical flow is simulated only between the layers; within each layer, modeled flow is two-dimensional. Modifications to the off-the-shelf model allow for (1) flow from the aquifer to springs and streams and from streams to the aquifer, (2) application of recharge to any layer, and (3) water-balance calculation for each layer.

In these early modeling efforts, steady-state simulations are effective tools because of their simplicity. Since the steady-state does not occur in nature, an instantaneous state was selected for simulations with the incorporation of recharge rate thought by the authors to be necessary to maintain that state. Small errors in estimated recharge can result in simulation of accurate potentiometric surfaces; if confining-bed leakance is adjusted.

Model simulation efforts for C06 and M09 followed a rule of first investigating the adequacy of simple models (those with identical hydrologic parameters in the top and middle units). Geologic similarity between the units, based on drill-hole data, indicated a possibility that these models will produce realistic simulations.

The ranges of hydrologic parameters used in reported simulations are:

Ground-water recharge = 0.5 ft/year
Aquifer hydraulic conductivity = 10^{-6} to 10^{-8} ft/sec
Leakance = 1.5 $(10)^{-9}$ to 10^{-11} Sec^{-1}
Spring and stream coefficients = 10^{-5} to 10^{-8} Sec^{-1}

Aquifer hydraulic conductivities used were those suggested by the results of aquifer test analyses. Confining-bed leakance ranged from a theoretical determined maximum to a minimum that simulated approximate impermeability.

Models with the same constant parameters for top and middle hydrologic units generate good simulations of C06 water levels, except in the eastern part of the top aquifer. In that area, a higher top confining-bed leakance could bring that simulated potentiometric surface into better agreement with field observations. For M09, an accurate simulation of observed water levels is achieved with a top aquifer hydraulic conductivity of 2 $(10)^{-7}$ ft/s or less, and with an areal variation in the top confining-bed leakance.

2. Unsaturated Flow Model

The unsaturated model has been formulated and the FORTRAN program has been written. This model is currently in an operational state on a stand-alone basis. It includes provision for evapotranspiration, and is capable of completely solving the water movement in individual prismatic elements. As it is incorporated into a composite model in the future, some minor modifications and enhancements are anticipated. A complete description of the mathematical formulation and the techniques used in obtaining the numerical solution of the unsaturated flow is given in the complete Phase I report, under the heading "Unsaturated Flow Model."

3. Overland Flow Model

The FORTRAN program of an overland flow model which solves the kinematic wave equations has been acquired, and effort has been made to make this program fully operational on a stand-alone basis. A number of routine type changes were necessary to "put the program up" on a different computer. At the present, there are difficulties in getting adequate performance from this program for some problem solutions that have been attempted. Future efforts will make the necessary modifications to get proper performance from the program, and thereafter couple it to other models.

4. Main Driving and Coupling Computer Program

A major effort will be required to develop the heart of the composite model; this is, the program that couples the separate component models and directs and coordinates their individual acivities so that complete and accurate simulation of the total

watershed hydrology is achieved. This driving and coordinating program will require a minimum of data to define its physical and hydrologic characteristics of the watershed being simulated, the characteristics of the simulation desired, and the type or form and extent of solution. As such it will:

a. Define the watershed's outline from limited, easily provided data.

b. Divide the watershed into appropriated prismatic elements for the unsaturated model.

c. From limited data easily obtained from a contour map and the water table elevations define the heights of each element.

d. Direct unsaturated solutions for some prismatic elements covering the ranges of conditions required within the watershed, and then by proper interpolation of these solutions determine water movement characteristics in the remaining elements.

e. Define the grid for use by the ground-water model, as well as the transmissivities at each of these.

f. Define recharge and discharge, constant head elements and the other boundary conditions for the ground-water model.

g. Coordinate the solutions of the separate models passing appropriate data from one model, when this data is needed as input.

h. Control and direct the simulation output as requested by the user.

The programming has been completed to accomplish items a. and b. above. The techniques for accomplishing these tasks are fully described in the complete Phase I report. Progress has been made on item d., and the remaining three items are planned for the future.

5. Defining Watershed Boundary

In order to simplify the data input required to define a watershed for simulation, computer software has been developed to generate data internally within the computer program in the form needed for the numerical solutions of the separate models from information that can easily be obtained. One such effort is the definition of the elements for use in the unsaturated and ground-water models by simply giving the x and y coordinates from selected points on the periphery of the watershed. These coordinates can be obtained readily from a map on which the watershed is outlined and then fitted by splines under tension. The details of splines under tension and how they are implemented are described in the complete Phase I report.

Appendix A

Parameters for which samples were analyzed

Sediment Fraction For Surface Water

Parameter

Calcium
Magnesium
Aluminum
Iron (total)
Manganese
Phosphorus (total)
Cadmium
Copper
Lead
Zinc
Nickel
Sodium
Strontium
Mercury
Sulfate
pH (lab)
TOC

Precipitation

Parameter

Aluminum
Antimony
Barium
Bicarbonate
Cadmium
Calcium
Conductance (sp.)
Copper
Hydrogen Sulfide
Iron
Lead
Magnesium
Manganese
Nickel
Nitrate (N)
pH (lab)
Phosphorus
Silver
Sodium
Strontium
Sulfate
Zinc

Surface Water

Parameter

Acidity
Alkalinity
Aluminum
Ammonia (N)
Antimony
Arsenic
Barium
Bicarbonate
Cadmium
Calcium
Carbon Dioxide
Chloride
Chromium
Color
Conductance (specific)
Copper
Cyanide
Fluoride
Hardness
Hydrogen sulfide
Iron
Lead
Magnesium
Magnese
Mercury
Nickel
Nitrate (N)
Oxygen (dissolved)
pH
Phenols
Phosphorus
Selenium
Silver
Sodium
Solids (susp.)
Solids (dissolved)
Strontium
Sulfate
Temperature
Zinc

Ground Water

Parameter

Alkalinity as $CaCO_3$
Aluminum (total)
Antimony (total)
Arsenic (total)
Barium (total)
Bicarbonate
Cadmium (total)
Calcium (dissolved)
Carbon Dioxide
Carbon (total organic)
Carbonate
Chloride (dissolved
Chronium (total)
Color
Conductance (sp.)
Copper (total)
Cyanide
Fluoride (dissolved)
Hardness (noncarbonate)
Hardness (total)
Hydrogen Sulfide
Iron (dissolved)
Iron (total)
Lead (total)
Magnesium (dissolved)
Manganese (dissolved)
Manganese (suspended)
Manganese (total)
Mercury (total)
Nickel (total)
Nitrogen (NH4) as total N
$NO_2 + NO_3$ as N
pH (field)
Phenols

Ground Water (Con.)

Parameter

Phosphorus as total P
Phosphorus as total PO_4
Potassium (dissolved)
Residue (dissolved-calculated sum)
Residue (dissolved)
Sodium absorption ratio
Selenium (total)
Silica (dissolved)
Silver (total)
Sodium (dissolved)
Sodium (percent)
Strontium (total)
Sulfate (dissolved)
Temperature (^0C)
Zinc (total)

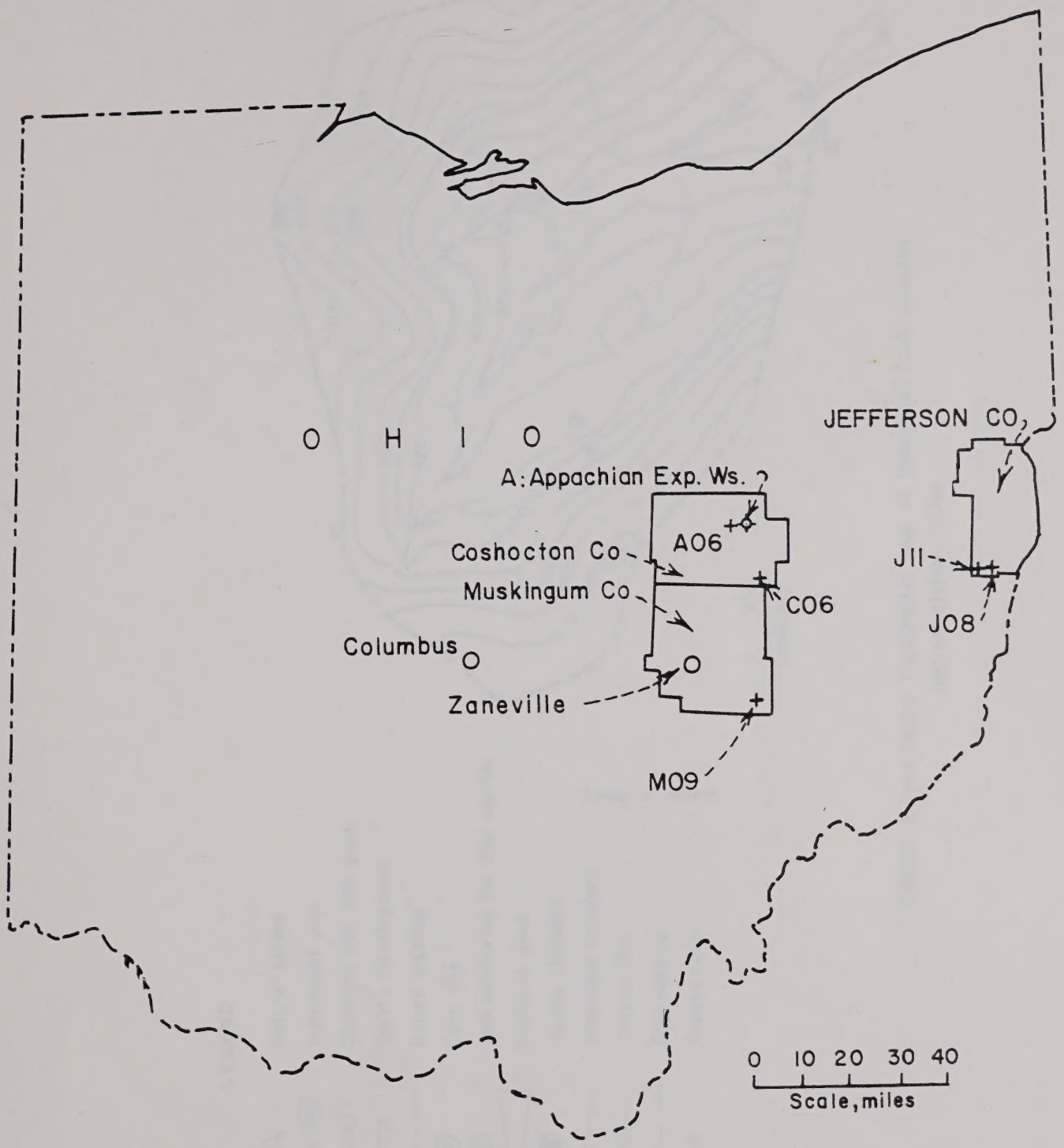


FIGURE 1.- Location of Study Sites

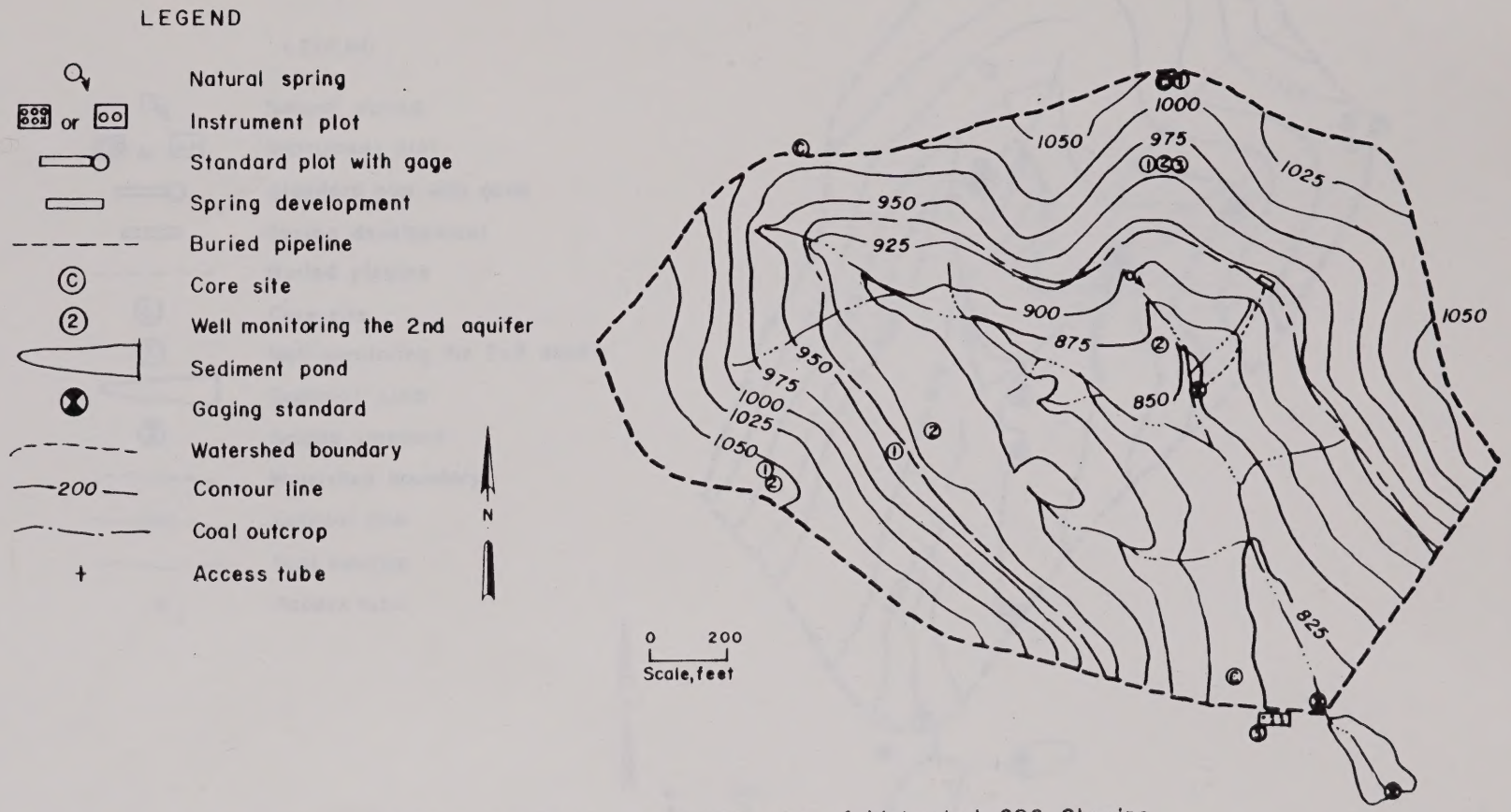


FIGURE 2.-Pre-mining Topographic Map of Watershed C06 Showing Instrumentation Sites

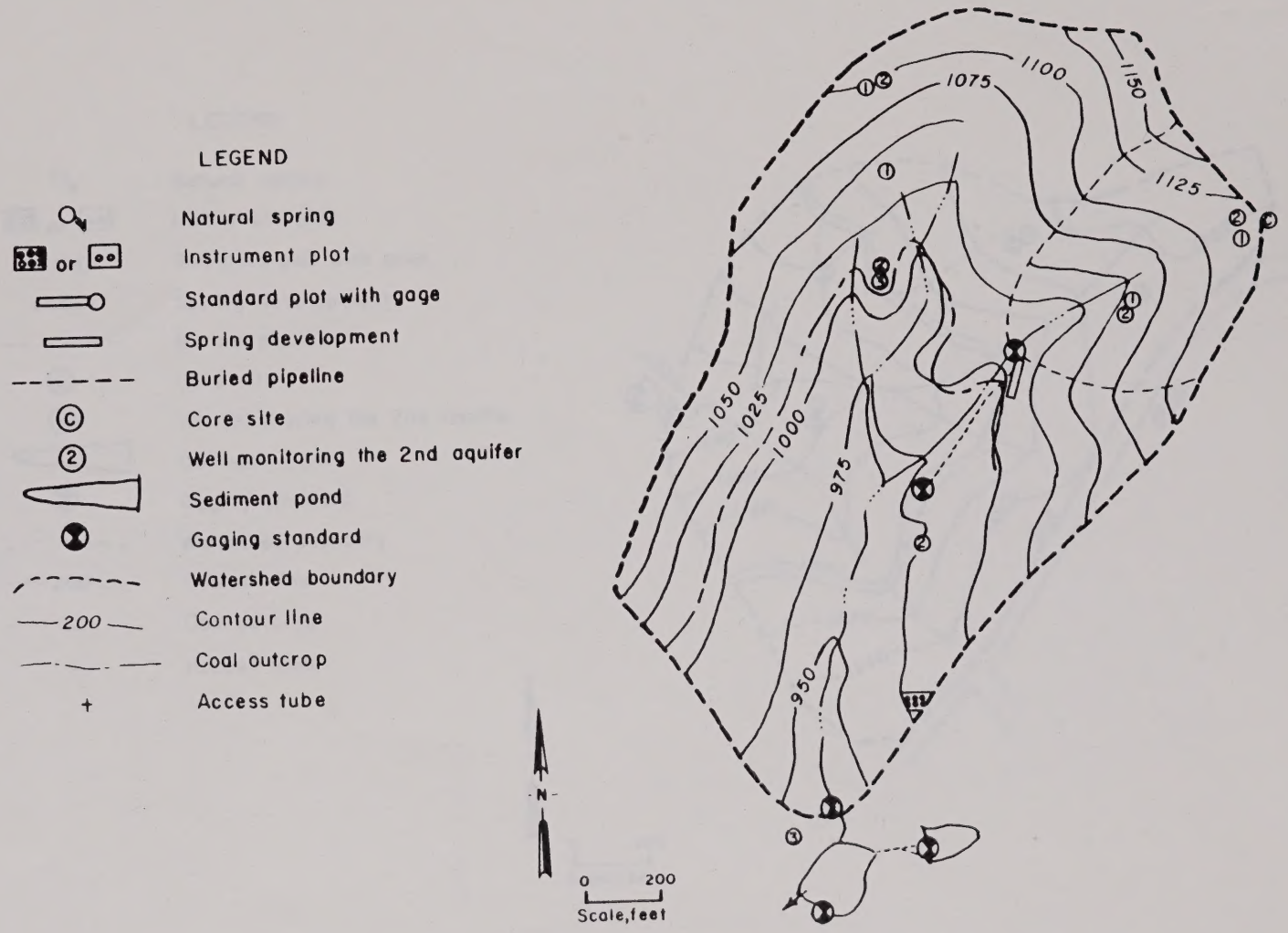


FIGURE 3.- Pre-mining Topographic Map of Watershed MO9 Showing Instrumentation Sites

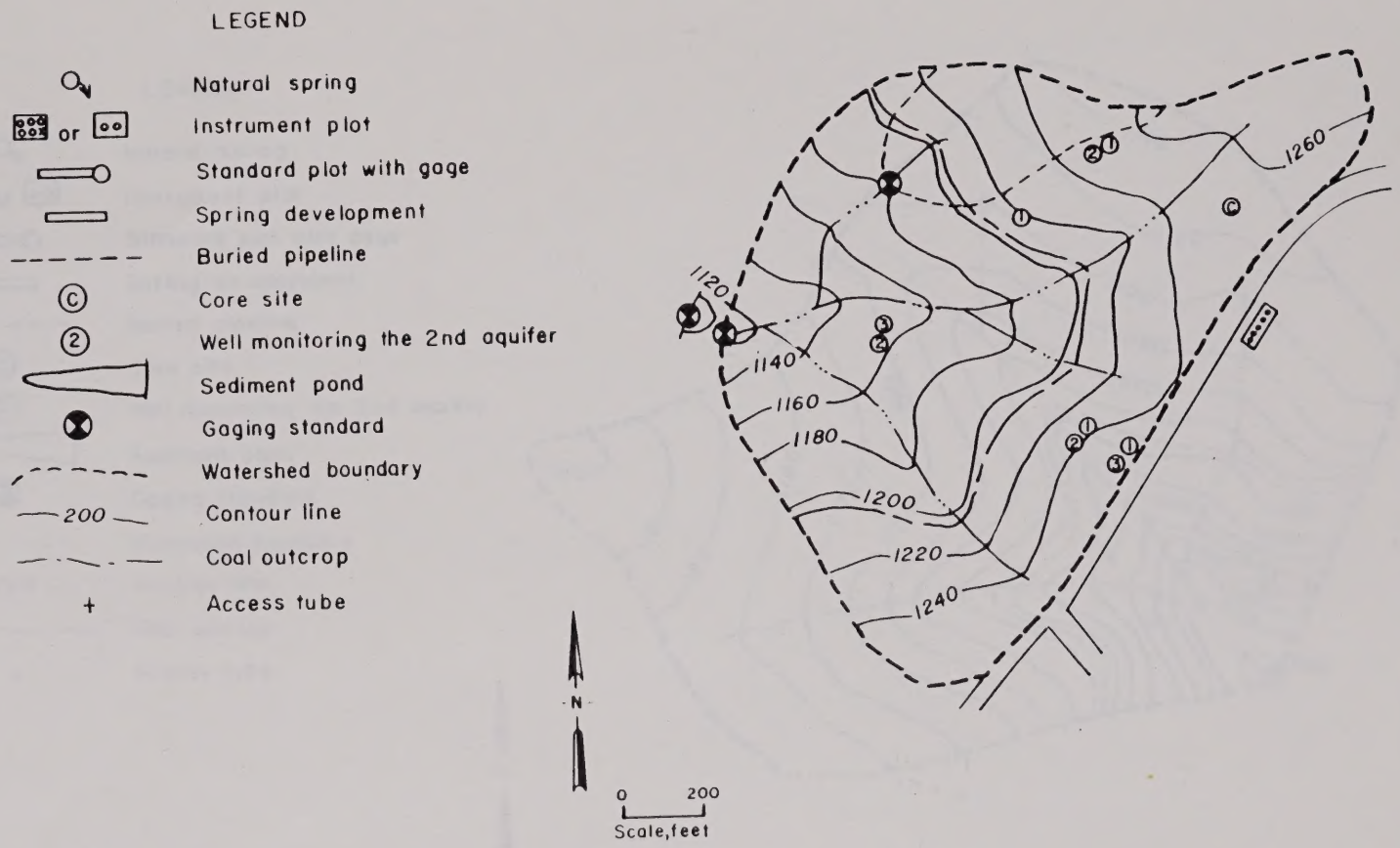


FIGURE 4.– Pre-mining Topographic Map of Watershed J11 Showing Instrumentation Sites

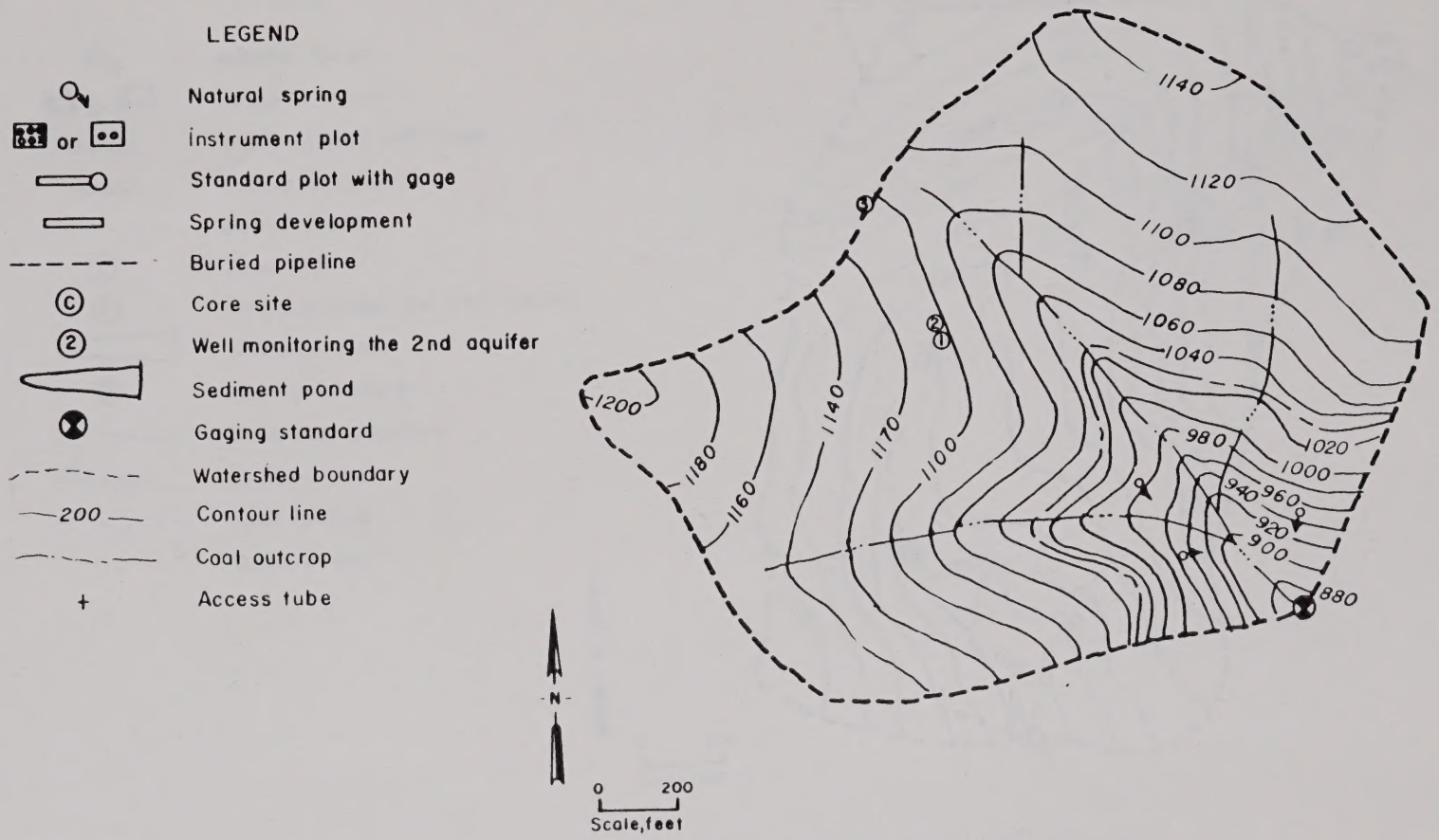


FIGURE 5.- Pre-mining Topographic Map of Watershed JO8 Showing Proposed and Existing Instrumentation Sites

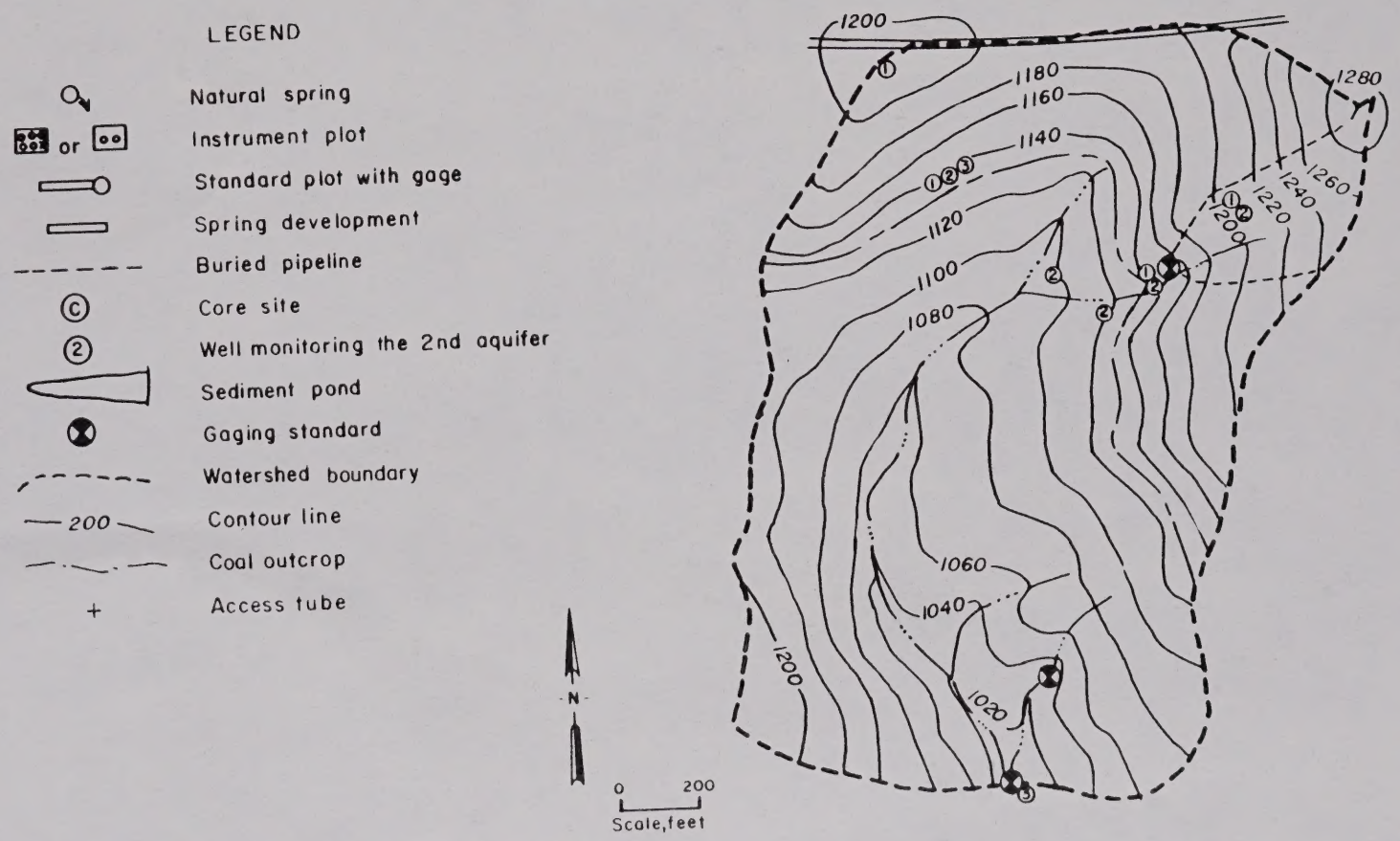
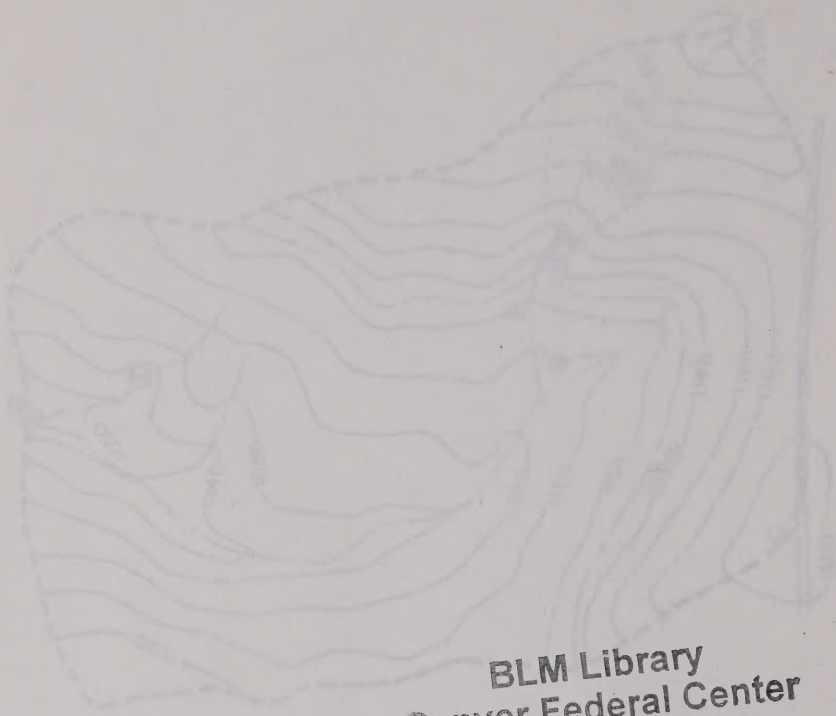


FIGURE 6.–Pre-mining Topographic Map of Watershed A06 Showing Instrumentation Sites



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